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Taylor, Philip E.

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Philip E. Taylor, PhD, and Haflidi Jonsson, PhD

Address
Division of Chemistry and Chemical Engineering,
California Institute of Technology, MC 210-41,
1200 E. California Boulevard, Pasadena, CA 91125, USA.
E-mail: taylor@caltech.edu

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Thunderstorms have often been linked to epidemics of asthma, especially during the grass flowering season; however, the precise mechanisms explaining this phenomenon are unknown. Evidence of high respirable allergen loadings in the air associated with specific meteorologic events combined with an analysis of pollen physiology suggests that rupture of airborne pollen can occur. Strong downdrafts and dry, cold outflows distinguish thunderstorm rain from frontal rain. The weather system of a mature thunderstorm likely entrains grass pollen into the cloud base, where pollen rupture would be enhanced, then transports the respirable-sized fragments of pollen debris to ground level where outflows distribute them ahead of the rain. The conditions occurring at the onset of a thunderstorm might expose susceptible people to a rapid increase in concentrations of pollen allergens in the air that can readily deposit in the lower airways and initiate asthmatic reactions.

Introduction

Changes in the weather have long been correlated with outbreaks of asthma. As early as the 12th century, the physician Moses Maimonoides recommended a dry climate for asthma sufferers. Throughout the past century, there have been numerous reports of asthma epidemics following thunderstorms, especially in Australia and the United Kingdom [1]. Thunderstorm asthma has been reported as a recurrent problem at several localities. More recent attempts at explaining the cause of these outbreaks have focused on the increased abundance of grass pollen in the air prior to a thunderstorm asthma event [2–11]. Correlations between high pollen counts and a thunderstorm-associated epidemic have also been observed in Canada [12] and Mexico [13].

Outdoor aeroallergens, such as pollen, are believed to play a role in asthma exacerbations [14,15]. In several studies, the use of skin prick testing and questionnaires from asthma patients submitted following a thunderstorm showed that nearly all those afflicted were allergic to rye-grass pollen [4,16,17]. Whole pollen is too large to deposit in the lower airways where asthmatic reactions arise; particles smaller than 5 μm are required [18]. Nebulized extracts of pollen debris elicit bronchospastic responses when inhaled by asthmatic patients [19]. Thunderstorm-associated asthma epidemics have also been correlated with peaks in fungal spore counts [12,20]. Researchers have long considered that if changes in the weather caused fragmentation of pollen and spores, generating allergen-laden aerosols as well as governing their release, then understanding the precise mechanisms involved in this link between asthma and the weather would be of great importance [21]. A step toward this was achieved by Taylor *et al.* [22••], who used controlled emission chamber experiments to show that pollen ruptures on the flower in high humidity and drying winds release respirable-sized particles of allergenic debris into the air.

Efforts to generate data on the abundance of specific respirable allergens in the atmosphere have been hampered by the lack of sampling instrumentation capable of accurate, time resolved immunoanalysis of airborne particles. Given this current limitation, to explain how a thunderstorm triggers an asthma epidemic, we compared the sequence of events involved in the formation and passage of a thunderstorm with conditions known to optimize the production and dispersal of respirable-sized, allergenic particles derived from biological sources, in particular, highly allergenic pollen and fungi.

Fungi emit a range of coarse particles into the air, such as spores and fragmented hyphae, as well as volatile compounds that account for their characteristic odors. The particulate emissions can be infectious agents (spores) or contain toxins and enzymes that act as irritants and allergens. Recent research shows that respirable fragments of cytoplasmic debris are released from the degenerating hyphae of allergenic fungi (*eg*, *Aspergillus* and *Alternaria*) [23,24•]. Fungi are more abundant in the outdoor air during and following warm, moist weather. Respirable-sized spores (*eg*, *Aspergillus*, *Aureobasidium*, *Cladosporium*, and *Penicillium*) are emitted when the fungi are disturbed by wind or the vibrations of impacting raindrops. Because pollen allergens are most implicated in thunderstorm asthma, this review is focused on explaining the likely mechanisms that result in enhanced pollen-allergen exposure to the lower airways of susceptible people at the onset of a thunderstorm.

Thunderstorm-associated Asthma Epidemic

The first emergency phone call for asthma generally occurs within 1 hour of a cold outflow, from an approaching

thunderstorm, reaching a populated district [25,26•]. Marks *et al.* [26•] believed that wind flow patterns concentrating allergens at tree level might maximize the exposure of susceptible people to allergen-loaded particles. They found a correlation between the incidence of outflows of colder air associated with the downdraft from a thunderstorm, an initial increase in ambient grass pollen counts, and the incidence of asthma epidemics. They hypothesized that outflows of cold air entrained pollen grains and particles and then concentrated them in a shallow band at ground level. They further suggest that these outflows, rather than electrical activity, thunder or rain alone, are responsible for the outbreak of asthma. In considering the origins of the respirable-sized allergenic particles, Marks *et al.* [26•] hypothesized that pollen is ruptured by rainfall at or near ground level and that the pollen debris is transported ahead of the rainfall by the outflow. According to this model, the available pollen would be entrained in the leading front of the cold, dry outflow prior to contact with rainfall. It would, therefore, not experience the conditions that would lead the pollen to rupture and release respirable allergens. Moreover, no mechanism by which an outflow of air can concentrate allergenic particles was provided.

Physiology of Pollen Rupture

In 1740, John Needham published the first observation of pollen rupture. He discovered that many types of pollen grains, upon being brought into contact with water, expand, extruding papillae at their pores, and eventually burst, discharging their contents. He believed the contents to be the fertilizing material. It was many years later that sperm cells and pollen tubes were observed. Today, pollen rupture is not considered to be functionally useful. Blackley [27] observed that water vapor can rupture pollen, and was the first to implicate pollen fragmentation in asthma and allergic disease. He believed that pollen ruptured on the mucous membranes, accounting for some of the phenomena of hay fever and asthma. He did not address how pollen fragments could aerosolize from the sticky secretions of mucus and saliva that entraps pollen.

There is now abundant evidence that pollen fragmentation plays a role in allergic disease, in particular as a potential trigger for asthma. Flowers have recently been identified as a source of fine particulate aerosols that contain pollen allergens [22••]. The flower anthers open when the relative humidity (RH) is reduced to less than 80%. Pollen grains from most wind-pollinating species remain on the open anthers until disturbed by wind or other forces. As the temperature decreases, humidity rises. When it exceeds a critical value, approximately 88% for rye grass, the anthers close. Grass and other allergic pollens (*eg*, trees and weeds) can then rupture on the flower at high humidity (> 96% RH). Subsequent drying winds may cause the anthers to reopen and entrain the allergenic pollen fragments in the air. These particles range in size from 30 nm to 4 μm, small enough to deposit in the lower airways. Understanding pollen physiology is crucial for predicting the environmental conditions that optimize pollen rupture and release respirable-sized allergenic particles into the air. Rain splash and vibrations from raindrops might release pollen from the flower, but they would be quickly scrubbed from the air.

Pollen has been detected in the atmosphere at high altitudes. Grass pollen may well rupture in the air, but direct observations are lacking. We have observed pollen rupture on a microscope slide when exposed to high humidity. With this mechanism, the flower anthers open once the humidity drops to approximately 80%; then, the mature pollen is ready to be released into the air when the wind disturbances arrive. Pollen has a fall rate of approximately 2 to 3.0 cm/sec, and, therefore, if the pollen is lofted above the surface, it may remain airborne for a long time. If the relative humidity (RH) increases above 96%, grass pollen can rupture and release its contents to form an aerosol of respirable-sized particles. Grass pollen only ruptures if it is viable (alive). Short exposures (2 hr) at RH less than 50% will kill the pollen and prevent rupture. At 80% RH, pollen can remain viable for 24 hours.

Pollen Allergens in the Atmosphere

Pollen allergens have been detected in the outdoor air in fine respirable particles since the 1980s using the immunolabeling methods of radioimmunosorbent assay (RAST) and enzyme-linked immunosorbent assay (ELISA). Pollen allergens have been recorded in aerosol fractions smaller than pollen grains, even when no pollen grains are present [28,29•,30–32]. Concentrations of these small allergenic particles increase after rainfall [28,29•]. Techniques for detecting airborne allergens remain poorly developed and are labor intensive. In one of the few quantitative studies performed to date, up to 15 ng/m^3 of grass group 1 allergen has been measured in airborne particles smaller than 7 μm that were collected on outdoor air filters after rainfall [29•]. However, it is likely that allergen levels were much higher because allergens bind avidly to filters and much is lost during elution. Asthmatic symptoms are observed in susceptible people throughout the grass flowering season after any moist weather conditions, not just during thunderstorms [32]. Rainfall scrubs the air of large (30 μm diameter) pollen grains, but raindrops produced by a mature thunderstorm are generally larger than 3 mm in diameter and do not efficiently remove particles smaller than 5 μm from the air [33].

Formation of a Thunderstorm

Thunderstorm development has previously been described in detail [34]. Here, we outline the growth and maturing stages. During thunderstorm growth, temperature and humidity are generally high at the ground, but temperature

decreases rapidly with altitude. Updrafts start developing at ground level, due to surface heating. Relative humidity increases in the rising air as temperature drops, until it reaches saturation and cloud formation begins (at altitudes that depend on the RH at the ground level). The heat released upon condensation of water vapor to form cloud droplets further increases buoyancy, causing the (now cloudy) updraft (or airflow) to accelerate. This continues as long as the temperature within the cloud is higher than that of the air surrounding the cloud. Hence, at this stage, the cloud is characterized by an updraft that is more or less uniform throughout the cloud.

As the cloud matures, precipitation begins to evolve in it. The first rain falling out of the cloud may evaporate and further increase the RH beneath the cloud. Associated with the falling rain is a downdraft, which is caused by the drag, exerted by the raindrops and by the cooling that takes place when the raindrops evaporate. At this stage, the following happens simultaneously: 1) Rain is falling, and RH is increasing to 100% beneath the cloud; 2) Cold downdrafts are occurring along with continuing updrafts that keep feeding warm, moist air into the cloud. These downdrafts become outflow when they reach the ground. Inside the cloud, the descending air cools due to evaporation. After leaving the cloud, continuing descent causes RH to decrease. As a result, the outflow areas are dry and cold. As the cold air moves out over warmer land, it becomes unstable, and enhances vertical mixing by turbulence.

Thus, the onset of rain raises humidity at the ground until it reaches 100%. Updrafts carrying air from the ground also increase RH until it reaches 100% at cloud base. The latter occurs before rain as well as after rain starts. Air exposed to high RH (perhaps 100%) gets caught in downdrafts and is then carried by the outflow far away from the rain. This is what distinguishes thunderstorm rain from frontal rain—the downdrafts and the dry, cold outflow.

Electrical Structure of Thunderstorms

The electric field begins to develop at about the same time as the precipitation [35]. Electric fields build on the ground to 5 to 10 kV/m where plants and other obtrusions initiate corona discharge. Positive ions thus drawn off the earth by the negative charge building in the lower part of the cloud quickly attach themselves to particles in the air. This causes the ions to quickly loose mobility. Thereafter, they move with the air—that is, after attachment to particles, their movement is not much affected by the electric forces. Lightning activity starts about this time.

Whether electrostatic forces induce release of pollen from anthers during a thunderstorm is unknown, but empirical evidence is suggestive. Studies in England and Wales associated high lightning activity with a 25% increased risk of asthma admission and more than 50-fold increased risk of asthma epidemics [8,9,36]. Pollen in the air will become charged by ions emitted from the ground. The charge may even induce pollen rupture. Moreover, electrostatic forces may cause pollen to be ruptured on the plant, but that needs to be investigated.

Proposed Mechanism for Thunderstorm Asthma

We propose an alternate hypothesis to explain thunderstorm-associated asthma epidemics (Fig. 1). Dry updrafts entrain pollen grains into the high humidity of the cloud base where they may rupture and release particles of cytoplasmic debris into the surrounding air. Then, downdrafts of cold air transport the pollen fragments to ground level in the dry, cold outflows away from the thunderstorm. The turbulent front of the moving outflow leads to further emission of pollen from flowering grasses. These emissions may then be entrained in dry updrafts and transported to the cloud base. Also, evaporating rain into which pollen has made its way may release pollen and pollen debris into the "background" air. This process increases the abundance of particulate allergens in the air. This is the most likely mechanism through which enrichment in concentration could take place. The likely chain of events is that pollen grains become enveloped by cloud droplets, either by serving as condensation nuclei or by diffusional attachment. Rupture of the pollen within the cloud droplet would result in the release of cytoplasmic debris into the water. Subsequent release of respirable allergenic particles would require a mechanism of fragmentation of the water droplet. Such fragmentation of overgrown raindrops occurs in clouds; the evidence of pollen allergen–induced asthma epidemics suggests it may be important.

Cold air and hypotonic water vapor are both known to induce bronchospasm, and by themselves may be a "factor of relevance" in thunderstorm asthma [37,38]. However, the equation of ruptured pollen fragments; small fungal particles; cold, humid air; and other meteorologic changes (such as changes in barometric pressure and air ionization) are all likely to interact to worsen asthma in individuals with hyperreactive airways.

The incidence of asthma outbreaks may vary with air pollution levels in the immediate environment. Pollen fragments and particles from fossil fuel combustion can deposit in similar regions of the lower airways. Pollutant particles may act as immunoadjuvants to allergen exposure. This may, in part, explain the increased incidence in allergic disease that has been documented over the past 50 years. Pollutant particles may also play a role in the larger thunderstorm-associated asthma epidemics occurring during very high allergen exposures.

Conclusions

We are beginning to understand the mechanisms involved in respirable-allergen aerosol formation and distribution during episodes known as thunderstorm asthma in so far

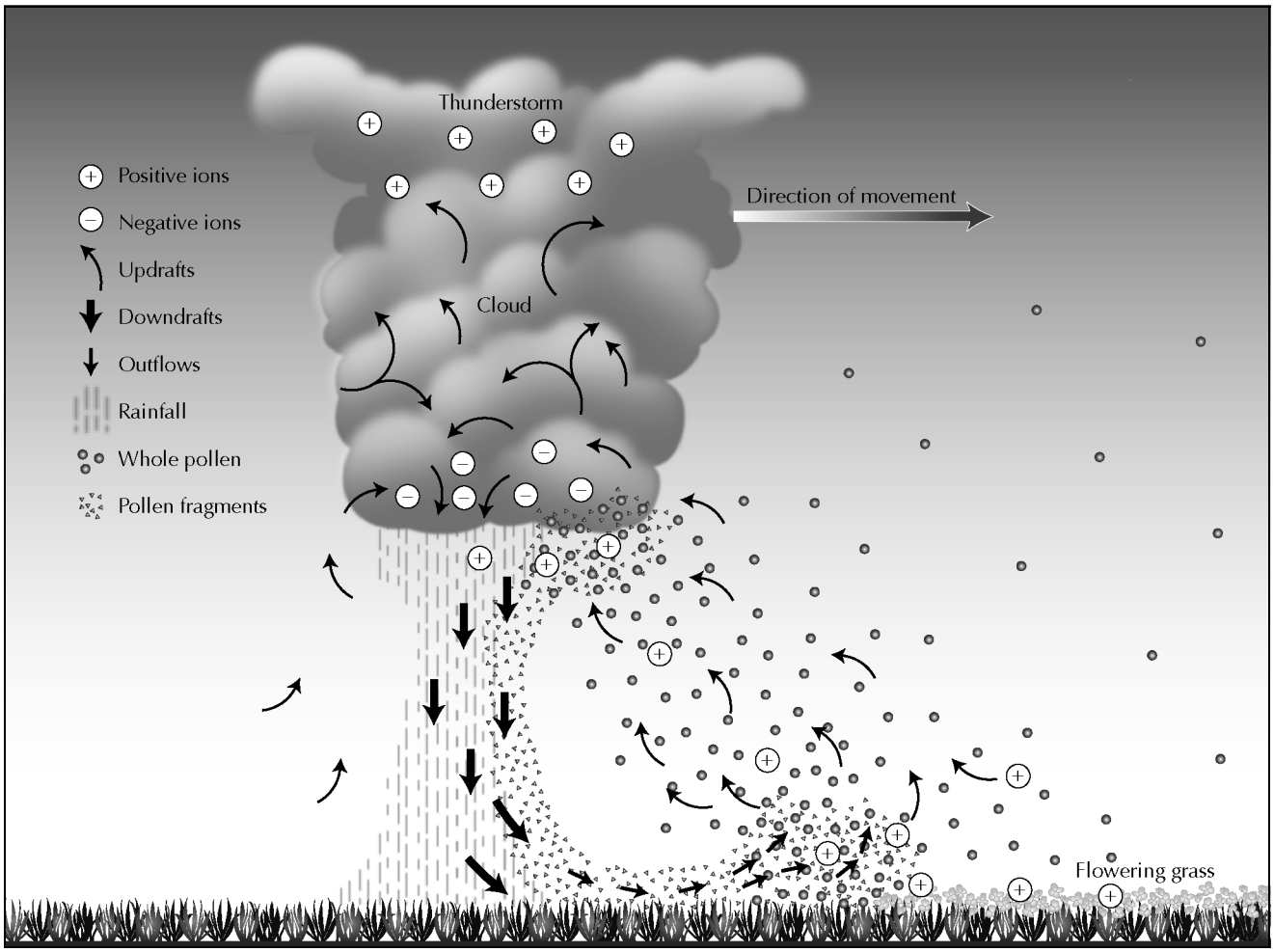

Figure 1. A proposed mechanism for explaining thunderstorm asthma. Dry updrafts entrain whole pollen grains into the high humidity at the cloud base of a maturing thunderstorm. Here, pollen may rupture, and cold downdrafts transport pollen fragments to ground level. Dry outflows distribute these respirable allergens at ground level and increase the exposure risks to humans. The turbulent front of the advancing outflow releases more pollen from flowering grasses, and then updrafts may entrain them into the cloud base. Strong electric fields develop in the thunderstorm. Positive ions are released from the ground and attach to particles entrained into the updrafts. Electric charge may enhance pollen rupture.

as pollens are involved. Both the updrafts and the cold downdrafts and outflows may play a role, along with rain and high humidity and (possibly) electrical activity, in enhancing pollen entrainment and subsequent rupture in the thunderstorm cloud base followed by transport and dispersal of fine allergenic aerosols of pollen debris near ground level. This combination of events may be responsible for epidemics of thunderstorm asthma. The focus of this article is on identifying and quantifying pollen allergens in the air with the temporal and spatial resolution required to determine the exposures that represent a risk to asthma sufferers. This will enable prediction of likely health outcomes from available weather forecasts and pollen and spore counts. Our proposed mechanism can now be tested in laboratory experiments and with the use of respirable-allergen detection in the outdoor air during a thunderstorm.

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References and Recommended Reading

Papers of particular interest, published recently, have been highlighted as:

- • Of importance
- •• Of major importance

1. Packe GE, Ayres JG: **Asthma outbreaks during a thunderstorm.** *Lancet* 1985, **27:**199–204.
2. Celenza A, Fothergill J, Kupek E, Shaw RJ: **Thunderstorm associated asthma: a detailed analysis of environmental factors.** *BMJ* 1996, **312:**604–607.
3. Davidson AC, Emberlin J, Cook AD, Venables KM: **A major outbreak of asthma associated with a thunderstorm: experience of accident and emergency departments and patients' characteristics. Thames Regions Accident and Emergency Trainees Association.** *BMJ* 1996, **312:**601–604.

4. Girgis ST, Marks GB, Downs SH, *et al.*: **Thunderstorm associated asthma in an inland town in southeastern Australia. Who is at risk?** *Eur Respir J* 2000, **16:**3–8.
5. Hajat S, Goubet SA, Haines A: **Thunderstorm-associated asthma: the effect on GP consultations.** *Br J Gen Pract* 1997, **47:**639–641.
6. Knox RB: **Grass pollen, thunderstorms and asthma.** *Clin Exp Allergy* 1993, **23:**354–359.
7. Lewis SA, Corden JM, Forster GE, Newlands M: **Combined effects of aerobiological pollutants, chemical pollutants and meteorological conditions on asthma admissions and A & E attendances in Derbyshire UK, 1993–1996.** *Clin Exp Allergy* 2000, **30:**1724–1732.
8. Newson R, Strachan DP, Archibald E, *et al.*: **Effect of thunderstorms and airborne grass pollen on the incidence of acute asthma in England, 1990–1994.** *Thorax* 1997, **52:**680–685.
9. Newson R, Strachan DP, Archibald E, *et al.*: **Acute asthma epidemics, weather and pollen.** *Eur Resp J* 1998, **11:**694–701.
10. Venables KM, Allitt U, Collier CG, *et al.*: **Thunderstorm-related asthma: the epidemic of 24/25 June 1994.** *Clin Exp Allergy* 1997, **27:**725–736.
11. Wark PAB, Simpson J, Hensley MJ, Gibson PG: **Airway inflammation in thunderstorm asthma.** *Clin Exp Allergy* 2002, **323:**1750–1756.
12. Wardman AE, Stefani D, MacDonald JC: **Thunderstorm-associated asthma or shortness of breath epidemic: a Canadian case report.** *Can Respir J* 2002, **9:**267–270.
13. Rosas I, McCartney HA, Payne RW, *et al.*: **Analysis of the relationship between environmental factors (aeroallergens, air pollution and weather) and asthma emergency admissions to a hospital in Mexico City.** *Allergy* 1998, **53:**394–401.
14. Fanta CH: **Fatal asthma and the environment.** *Immunol Allergy Clin North Am* 2002, **22:**911–924.
15. Frei T: **Pollenasthma in der Schweiz von 1993 bis 1997.** *Allergologie* 1999, **22:**382–387.
16. Bellomo R, Gigliotti P, Treloar A, *et al.*: **Two consecutive thunderstorm-associated epidemics of asthma in the city of Melbourne: the possible role of rye grass pollen.** *Med J Aust* 1992, **156:**834–837.
17. Packe GE, Ayres JG: **Aeroallergen skin sensitivity in patients with severe asthma during a thunderstorm.** *Lancet* 1986, **12:**850–851.
18. Chan TL, Lippmann M: **Experimental measurements and empirical modelling of the regional deposition of inhaled particles in humans.** *Am Ind Hyg Assoc J* 1980, **41:**399–405.
19. Suphioglu C, Singh MB, Taylor PE, *et al.*: **Mechanism of grass-pollen-induced asthma.** *Lancet* 1992, **399:**569–572.
20. Dales RE, Cakmak S, Judek S, *et al.*: **The role of fungal spores in thunderstorm asthma.** *Chest* 2003, **123:**745–750.
21. **Editorial: Asthma and the weather.** *Lancet* 1985, **8437:**1079–1080.
22.•• Taylor PE, Flagan R, Valenta R, Glovsky MM: **Release of allergens in respirable aerosols: a link between grass pollen and asthma.** *J Allergy Clin Immunol* 2002, **109:**51–56.

Observed grass flowers to be a site of pollen rupture, and used controlled emission experiments to generate and characterize aerosols of allergenic pollen debris from flowers.

23. Glovsky MM, Taylor PE, Esch R, *et al.*: **Respirable allergenic aerosols produced from pollen and molds.** In *Asthma: From Genes to Clinical Management.* Edited by Sepiashvili R. Bologna, Italy: Monduzzi Editore; 2003:155–160.
24.• Gorny RL, Reponen T, Willieke K, *et al.*: **Fungal fragments as indoor air biocontaminants.** *App Environ Micro* 2002, **68:**3522–3531.

Detected respirable-sized fragments emitted from a fungal colony housed within a controlled-emission chamber.

25. Higham JH: **Asthma trends: thunderstorm peak in Luton.** *BMJ* 1994, **309:**604.
26.• Marks GB, Colquhoun JR, Girgis ST, *et al.*: **Thunderstorm outflows preceding epidemics of asthma during spring and summer.** *Thorax* 2001, **56:**468–471.

Correlated the incidence of thunderstorm outflows with an increase in grass pollen abundance and epidemics of asthma affecting grass pollen sensitive patients.

27. Blackley CH: *Experimental Researches on the Causes and Nature of Catarrhus Aestivus (Hay Fever or Asthma).* London: Balliere, Tindall and Cox; 1873.
28. Pehkonen E, Rantio-Lehtimaki A: **Variations in airborne pollen antigenic particles caused by meteorologic factors.** *Allergy* 1994, **49:**472–477.
29.• Schäppi G, Taylor PE, Pain MCF, *et al.*: **Concentrations of major grass group 5 allergens in pollen grains and atmospheric respirable particles: implications for hayfever and allergic asthma sufferers sensitised to grass pollen allergens.** *Clin Exp Allergy* 1999, **29:**633–641.

Collected respirable-sized particles on outdoor air filters and performed immuno-analysis in an attempt to quantify the presence of grass group 1 allergens.

30. Spieksma FTM, Kramps JA, Van der Linden AC: **Evidence of grass pollen allergenic activity in the smaller micronic atmospheric aerosol fraction.** *Clin Exp Allergy* 1990, **20:**273–280.
31. Spieksma FTM, Nikkels BH, Dijkman JH: **Seasonal appearance of grass pollen allergen in natural pauci-micronic aerosol of various size fractions: relationship with airborne grass pollen concentration.** *Clin Exp Allergy* 1995, **25:**234–239.
32. Staff IA, Schaeppi G, Taylor PE: **Localisation of allergens in rye-grass pollen and in airborne micronic particles.** *Protoplasma* 1999, **208:**47–57.
33. McDonald JE: **Collection and washout of airborne pollens and spores by raindrops.** *Science* 1962, **135:**435–436.
34. Byers HR, Braham RR: *The Thunderstorm: Report of The Thunderstorm Project.* Washington, DC: US Dept of Commerce; 1949.
35. Krehbiel PR: **The electrical structure of thunderstorms.** In *The Earth's Electrical Environment.* Washington, DC: National Academy Press: 1986:90–113.
36. Higham J, Venables K, Kupek E, *et al.*: **Asthma and thunderstorms: description of an epidemic in general practice in Britain using data from a doctors' deputising service in the UK.** *J Epidemiol Comm Health* 1997, **51:**233–238.
37. Bibi H, Nutman A, Shoseyov D, *et al.*: **Prediction of emergency department visits for respiratory symptoms using an artificial neural network.** *Chest* 2002, **122:**1627–1632.
38. Hashimoto M, Fukuda T, Shimizu T, *et al.*: **Influence of climatic factors on emergency visits for childhood asthma attack.** *Pediatr Int* 2004, **46:**48–52.